W mass measurements in ATLAS experiment at the LHC

Tairan Xu, Mengran Li, Xuewei Jia, Junjie Zhu, Joao Guimaraes da Costa

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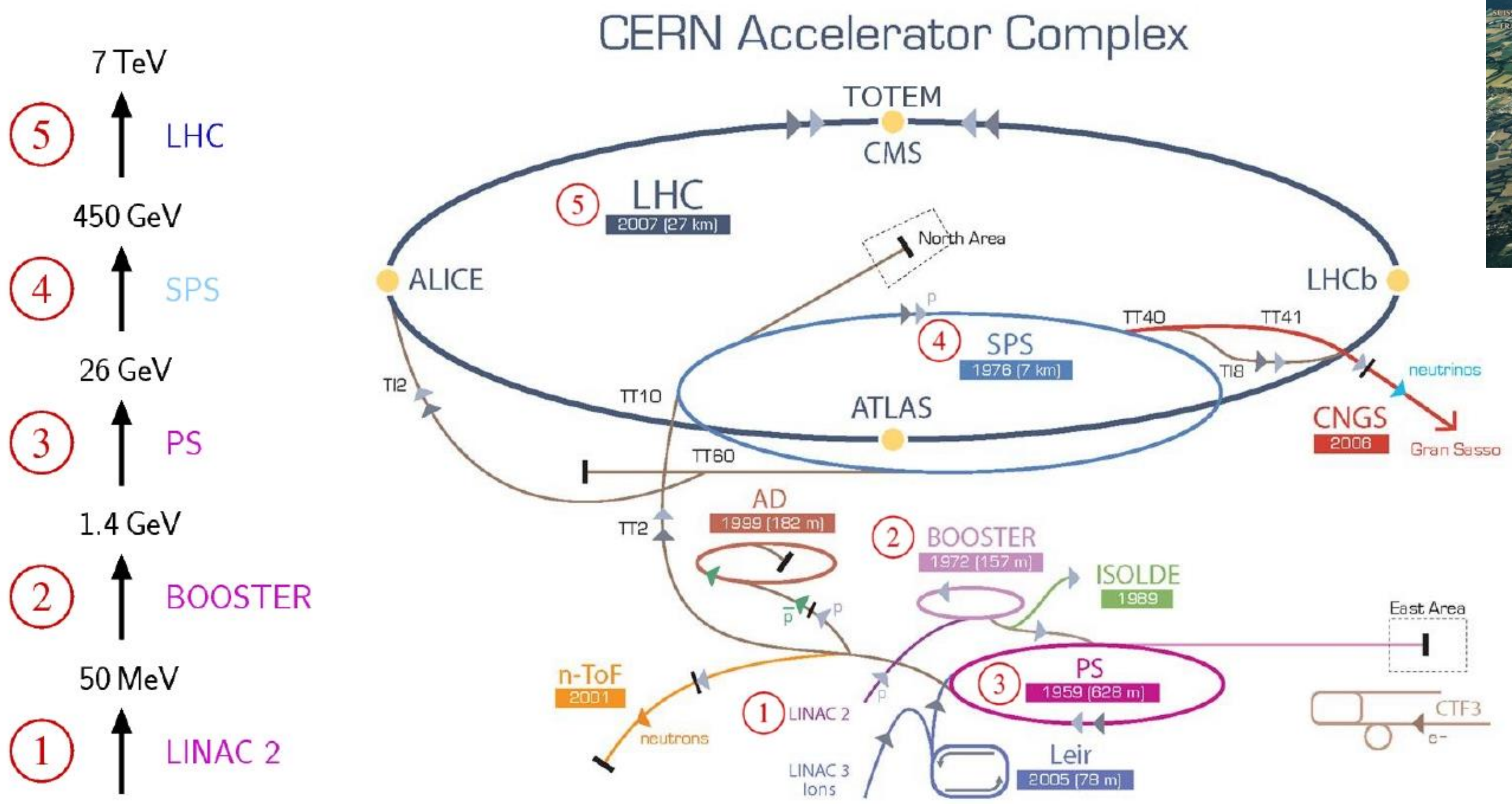
Institute of High Energy Physics
Chinese Academy of Sciences

UNIVERSITY OF MICHIGAN

Outline:

- **Introduction**
- **W-mass measurement using LHC Run-I data**
- **W mass @ ATLAS Run-II & future prospects**

LHC & ATLAS



Proton-proton collider working at $\sqrt{s}$ = 2.76, **5**, **7**, 8, **13** TeV

W mass

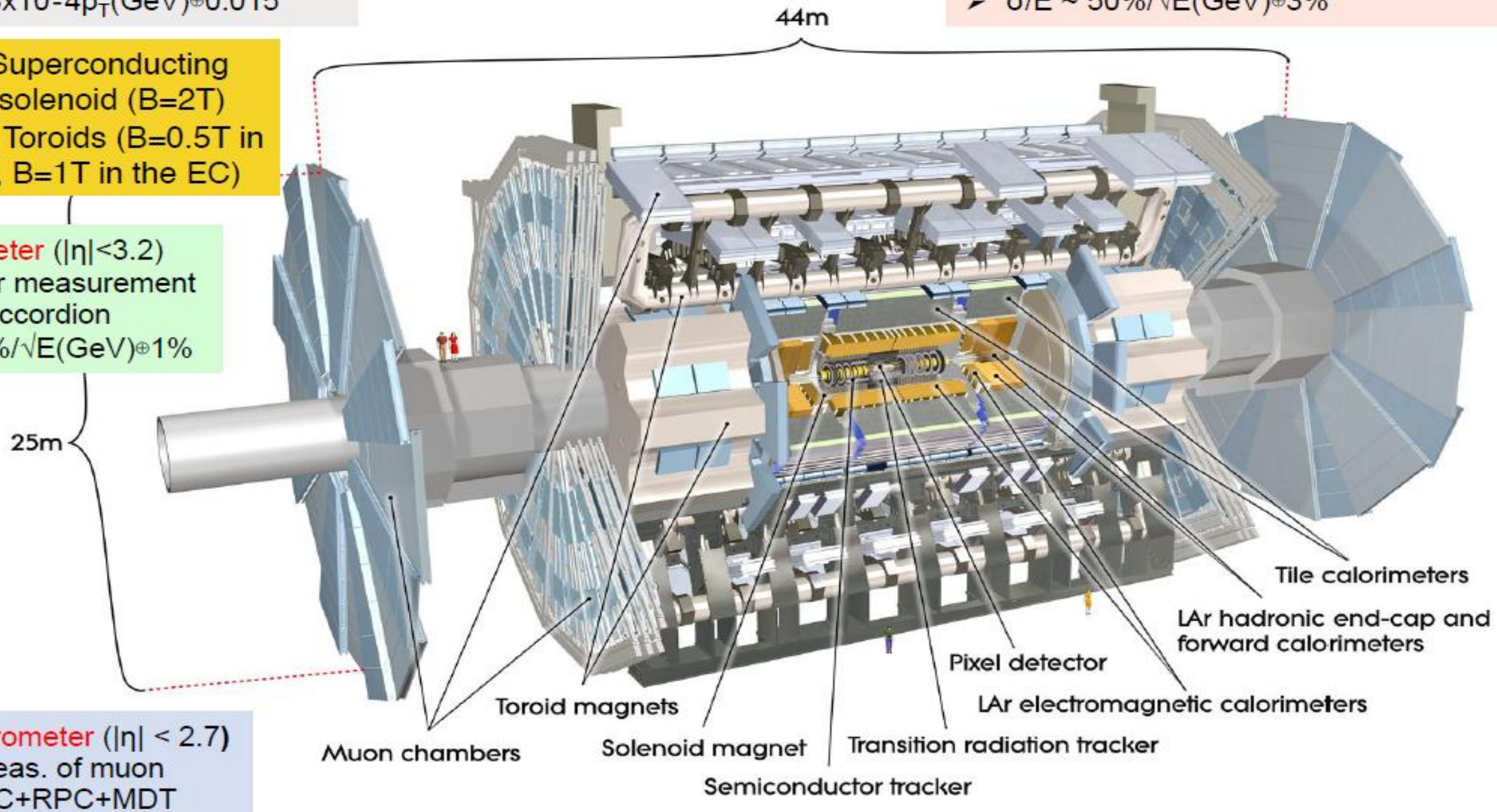
LHC & ATLAS

Inner detector ($|\eta| < 2.5$, B=2T)
Tracking, vertexing, dE/dx, e/π ID
- Si pixels, Si strips, Trans. Rad. det.
- $\sigma/p_T \sim 3.8 \times 10^{-4} p_T(\mathrm{GeV}) \oplus 0.015$

Hadron Calorimeter ($|\eta|<5$)
Trigger and meas. of jet/Emiss
- Fe/scintillator (central), Cu/W-LAr (fwd)
- $\sigma/E \sim 50\%/\sqrt{E(\mathrm{GeV})} \oplus 3\%$

4 Magnets Superconducting
- 1 Central solenoid (B=2T)
- 3 Air core Toroids (B=0.5T in the barrel, B=1T in the EC)

EM Calorimeter ($|\eta|<3.2$)
e/γ ID trigger measurement
- Pb-Lar accordion
- $\sigma/E \sim 10\%/\sqrt{E(\mathrm{GeV})} \oplus 1\%$

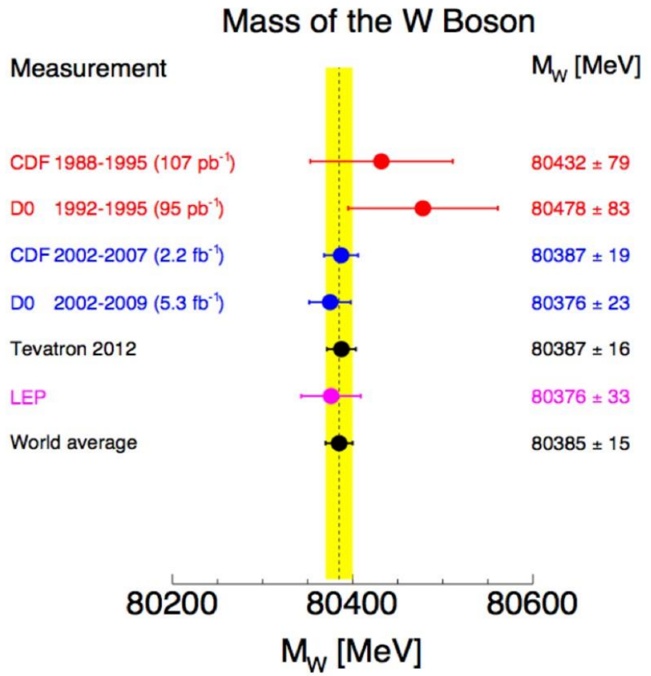


Muon spectrometer ($|\eta| < 2.7$)
Trigger & meas. of muon
- CSC+TGC+RPC+MDT
- σ/p_T <10 % up to 1 TeV

Before the ATLAS Run-I W-mass measurement

	Measurement	SM Prediction (*)
m_H	125.09 ± 0.24	102.8 ± 26.3
m_{top}	172.84 ± 0.70	176.6 ± 2.5
m_W	80.385 ± 0.015	80.360 ± 0.008

(*) arXiv:1608.01509



Before ATLAS

The direct measurements of M_t and M_H are more accurate than indirect determination (from EW global fit).

→ The sensitivity of new physics will not increase with precision

Indirect W mass (±8 MeV) is more precise than the experimental result!

→ Call for δM_W < 10 MeV!

The measured W mass is the crucial parameter to the sensitivity of the global EW fits to new physics

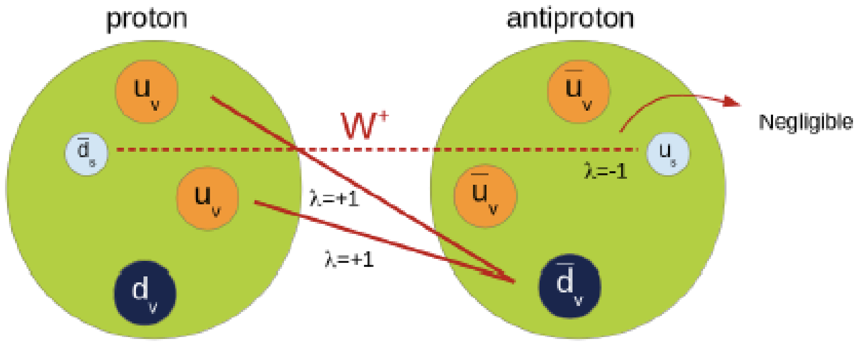
W mass @ LHC

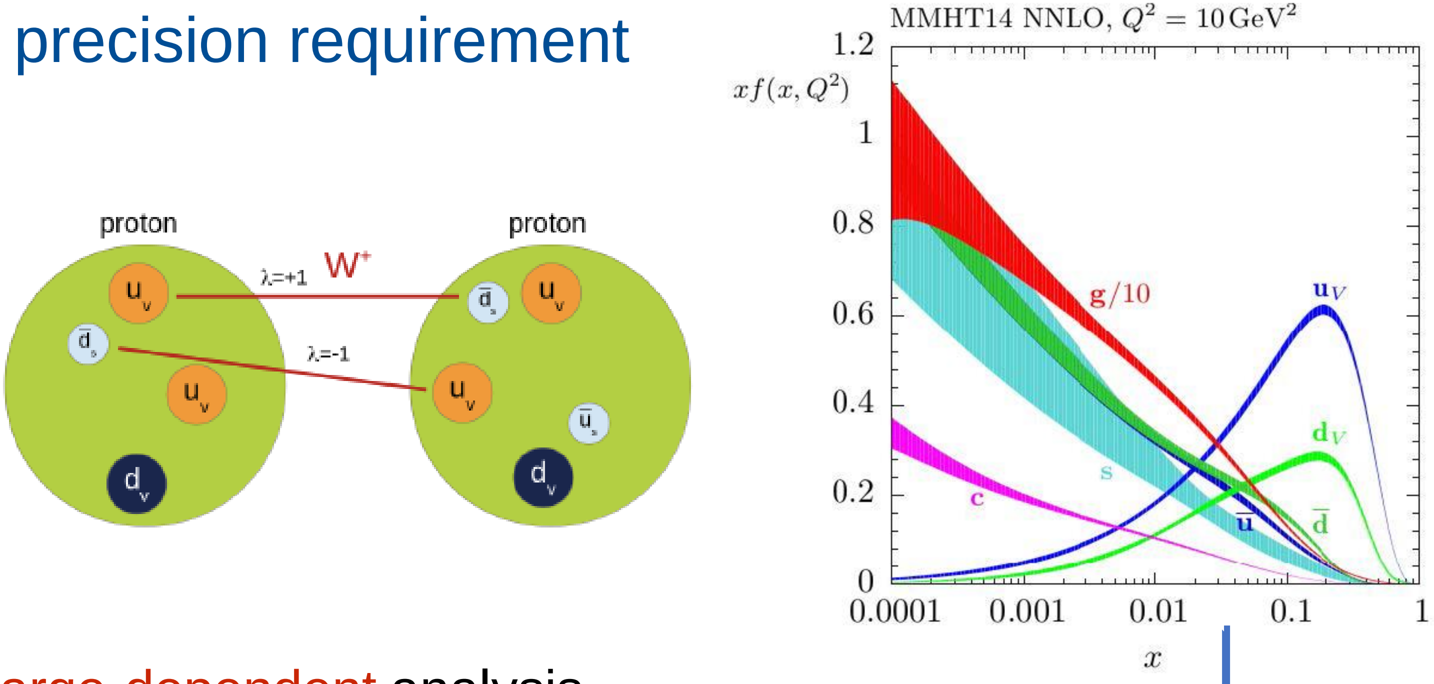
*pileup introduced in later section

Challenging environment @LHC:

Pileup* induced high experimental precision requirement

Accurate theoretical modelling





- W+/W- production is asymmetric -> charge-dependent analysis
- Second generation quark PDFs play a larger role at the LHC *(25% of the Wboson production is induced by at least one second generation quark s or c).*
- The W polarization is determined by the difference between the u,d valence and sea densities

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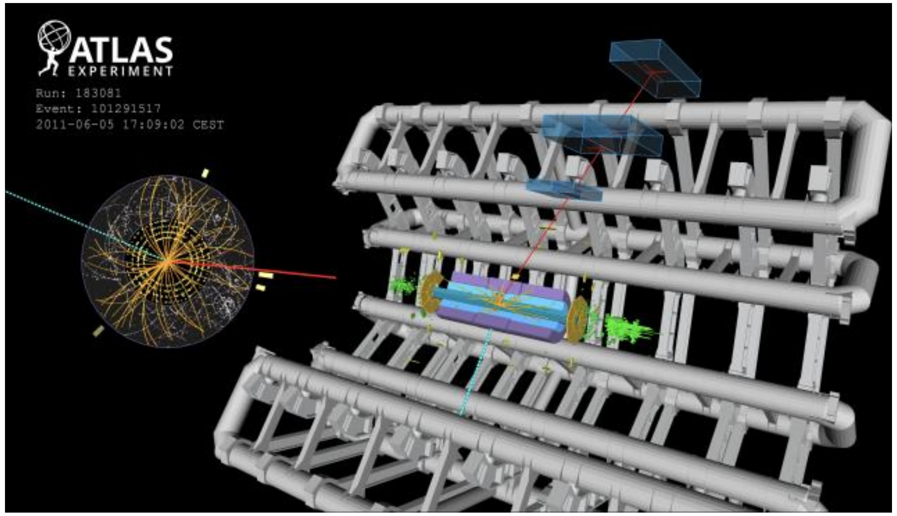
First W mass measurement at the LHC

published in EPJC Eur.Phys.J.C (2018) 78:110



CERN Courier January/February 2017

News

LHC EXPERIMENTS

ATLAS makes precision measurement of W mass

CERN Accelerating science

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First high-precision LHC measurement of W boson mass

The Guardian International edi

Tribune de Genève

SWI swissinfo.ch

ASTROPAGE.EU

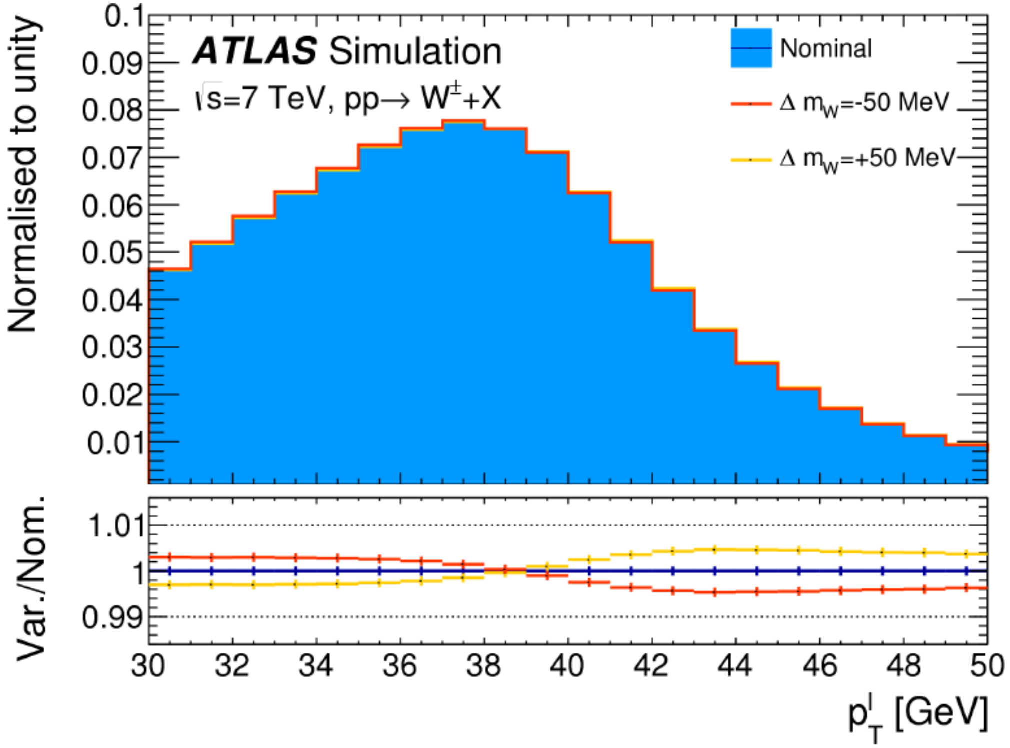
How to measure W mass?

minimal χ^2(Likelihood) approach for Run I (Run II)

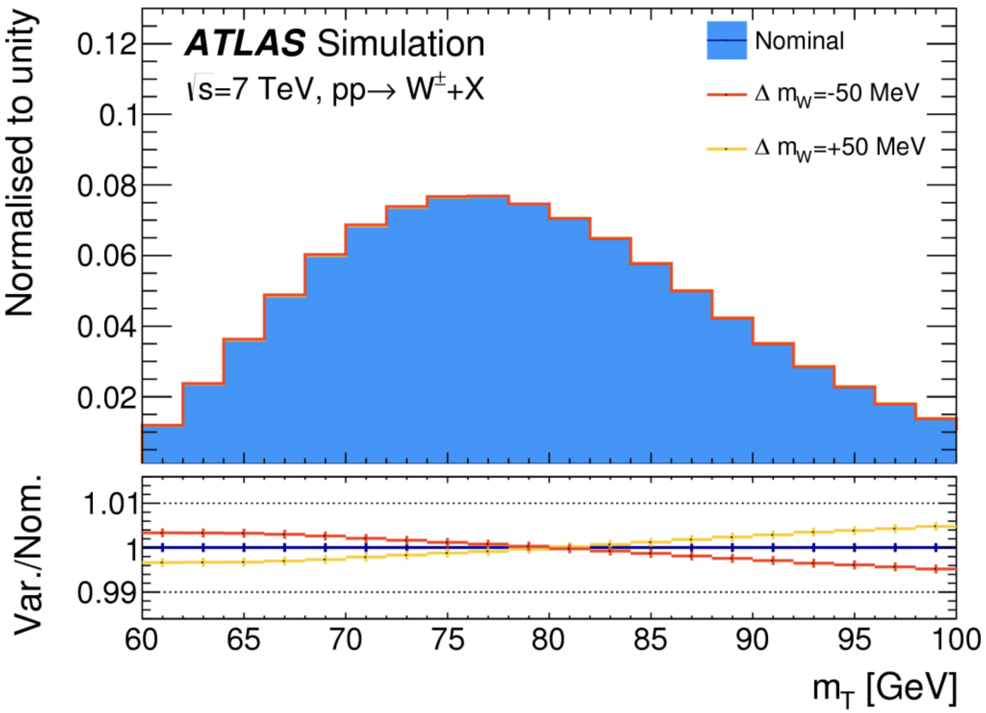
Template fit approach using m_W templates based on BW function:

$$\frac{d\sigma}{dm} \propto \frac{m^2}{(m^2 - m_V^2)^2 + m^4\Gamma_V^2/m_V^2}$$

p_T^l has a Jacobian edge at $m^W/2$



m_T^W has a Jacobian edge at m^W

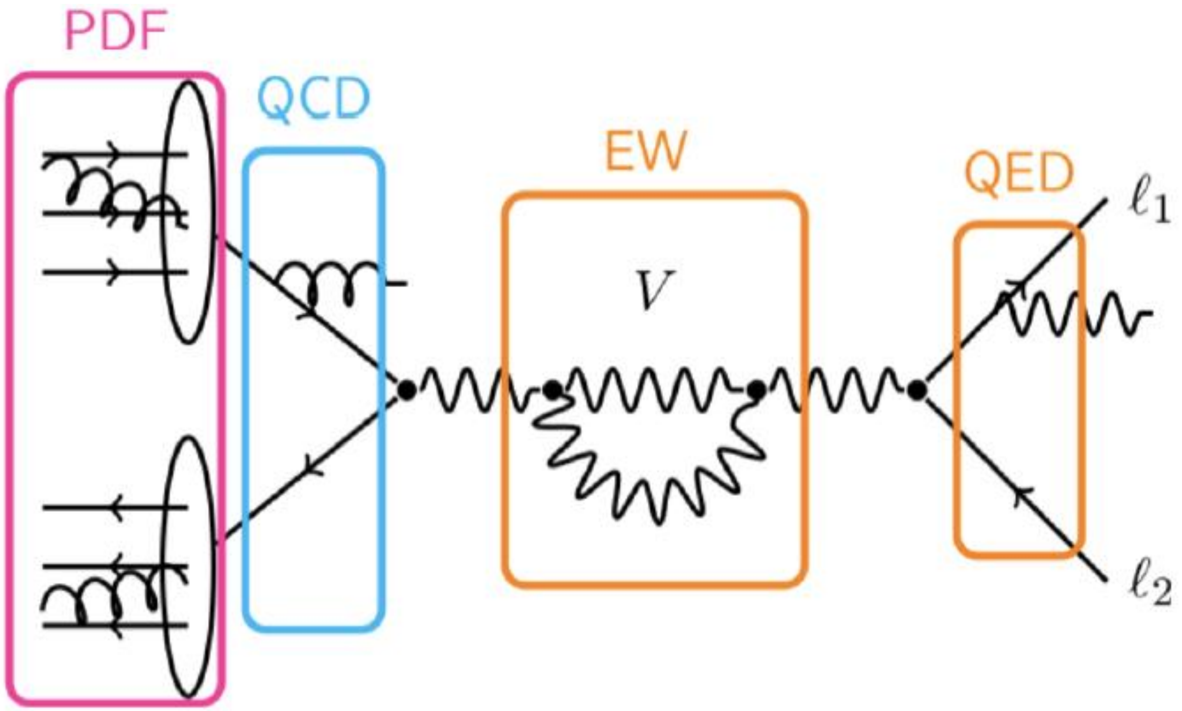


A blinding offset *was applied throughout the measurement and removed when consistent results were found.*

Physics modelling:

The approach of prediction to data is essential in W mass measurements.

Start from the Powheg+Pythia8 and apply corrections.
Ancillary measurements of W/Z for validation and systematics.



EW corrections:
- **QED FSR / ISR**
- **Higher order effects/ FSR pair production**

QCD corrections:
- **Polarization**
- **Rapidity**
- **Transverse momentum**

Physics modelling:

An approximate decomposition of Drell-Yan is given by factorizing the dynamic of boson production and the kinematic of boson decay:

$$\frac{d\sigma}{dp_1\, dp_2} = \left[\frac{d\sigma(m)}{dm}\right]\left[\frac{d\sigma(y)}{dy}\right]\left[\frac{d\sigma(p_T, y)}{dp_T\, dy}\left(\frac{d\sigma(y)}{dy}\right)^{-1}\right]\left[(1+\cos^2\theta) + \sum_{i=0}^{7} A_i(p_T, y) P_i(\cos\theta, \phi)\right]$$

Breit-Wigner

NNLO pQCD

Parton Shower

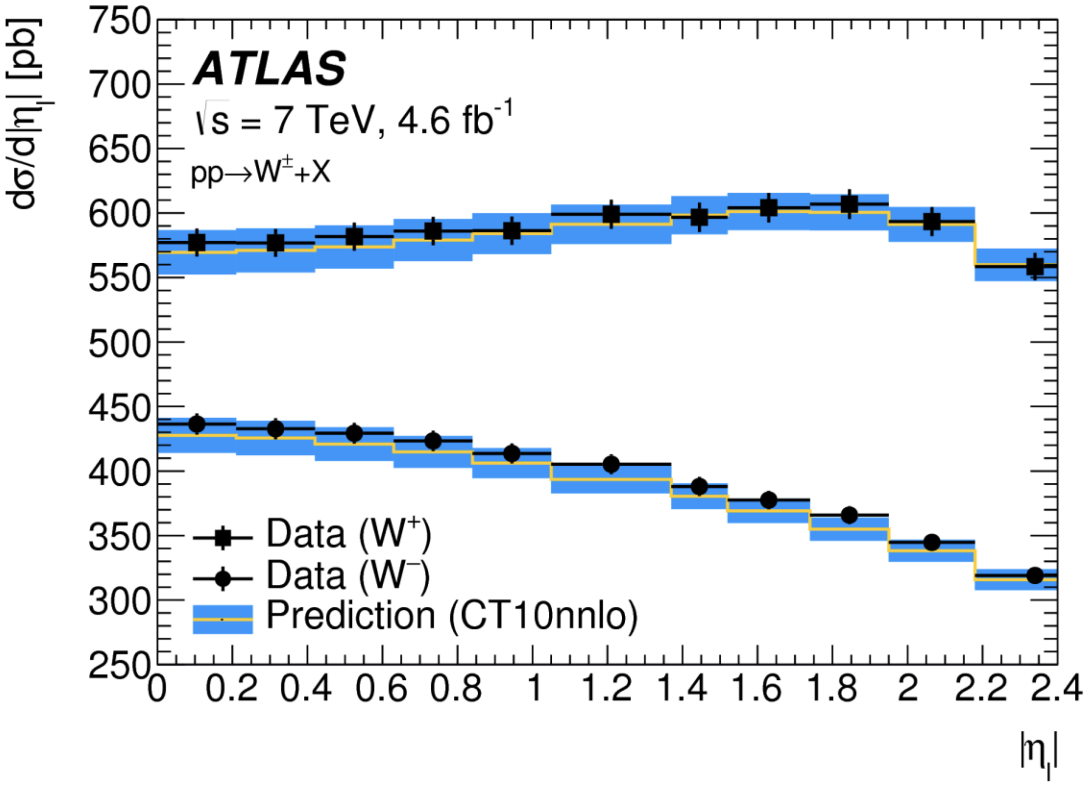
MC:
- Powheg+Pythia8, CT10NNLO
- Sherpa, NNPDF3.0 + MEPS@NLO

EW:
- Photos + Pythia8
- winhac

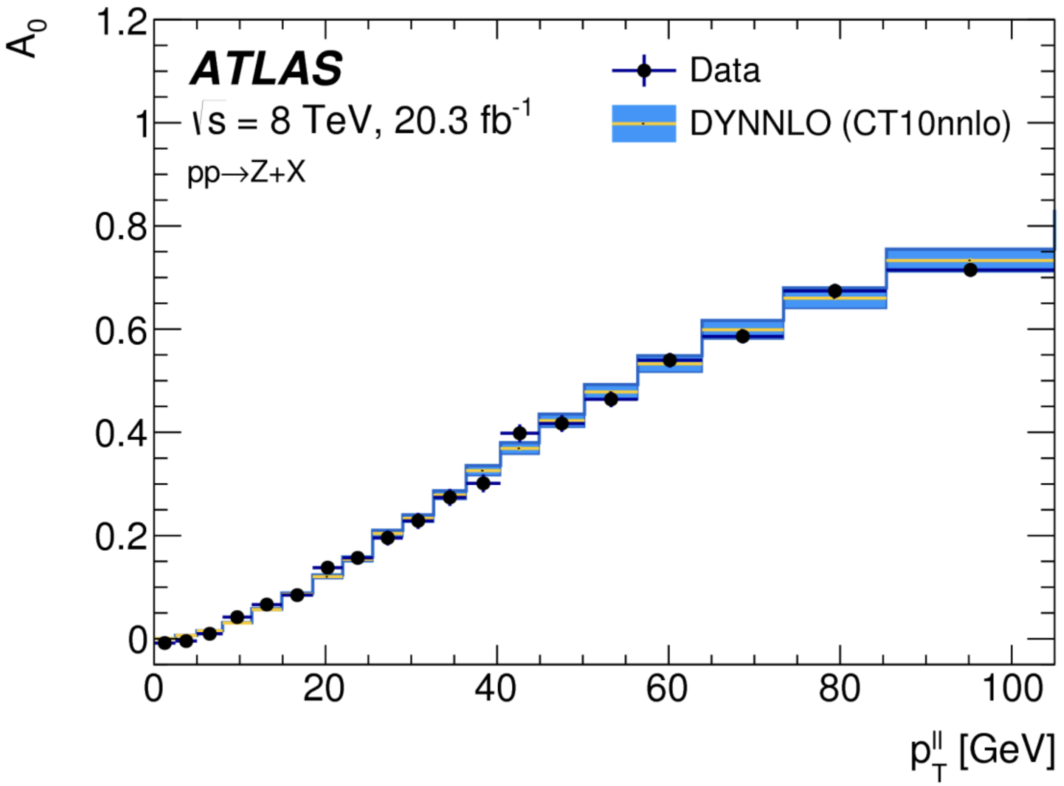
- Breit-Wigner parameterization: $\frac{d\sigma}{dm} \propto \frac{m^2}{(m^2 - m_V^2)^2 + m^4\Gamma_V^2/m_V^2}$
- $d\sigma/dy$: modelled with fixed order pQCD at NNLO, arXiv:1612.03016
- $d\sigma/dp_T$: modelled with parton shower
- $A_i, i = 0 \ldots 7$: Angular coefficients, model the polarization state of vector boson, JHEP08(2016)159

Rapidity and Angular coefficients

Modelled with fixed order pQCD at NNLO (CT10nnlo pdf), arXiv:1612.03016



Agreement satisfied between the theoretical prediction and the experimental observation: χ^2/dof = 45/34.



Prediction (DYNNLO) validated by to the 8-TeV Z boson Ai measurement: JHEP08(2016)159

p_T^W , transverse momentum

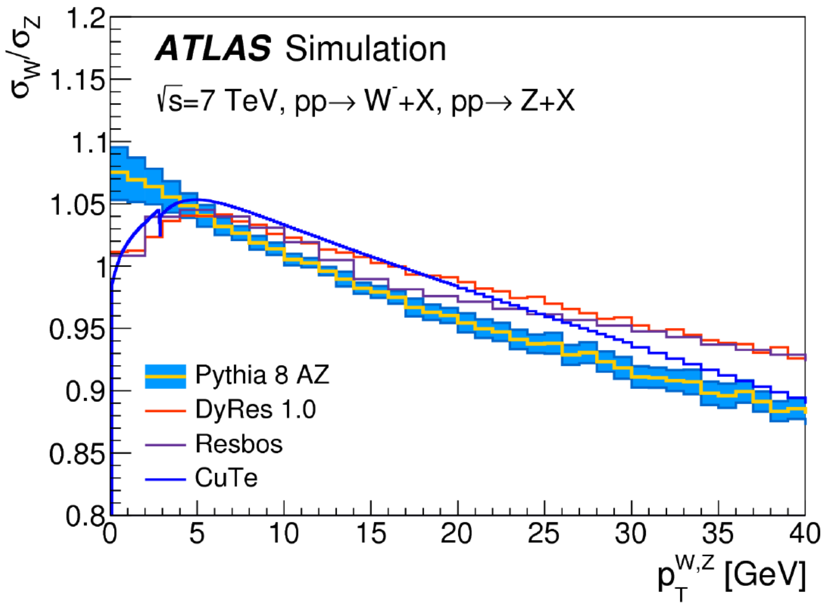
Most efforts in modelling p_T^W:

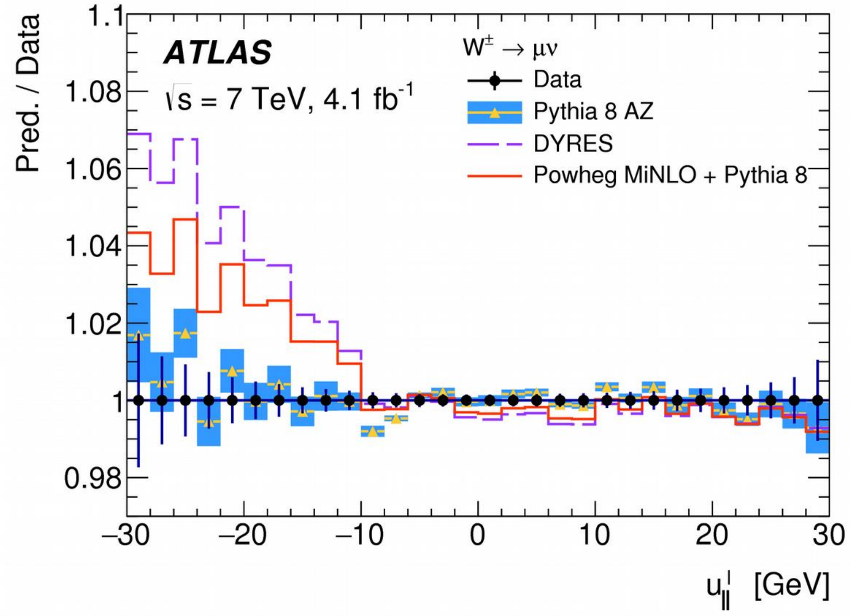
Baseline: Pythia8 AZ tune (fixed by the p_T^Z measure), extrapolated to p_T^W , considering related variations in p_T^W/ p_T^Z JHEP09(2014)145

- Resummed NNLL predictions (DYRES, ResBos, CuTe) were tried but mis-modeled at low pT. Phys.Rev.D 50 (1994) R4239, Phys.Rev.D 56 (1997) 5558-5583, JHEP12 (2015)047, JHEP03 (2011) 032, JHEP10 (2012) 155, JHEP05 (2013) 082…
- Using "formally" predicted p_T^W will impact the W-mass precision by 50-100 MeV

p_T^W validated with the recoil distribution .

truth-level





Uncertainties in the physics modelling

EW

Decay channel	$W \to e\nu$		$W \to \mu\nu$	
Kinematic distribution	p_T^ℓ	m_T	p_T^ℓ	m_T
δm_W [MeV]				
FSR (real)	< 0.1	< 0.1	< 0.1	< 0.1
Pure weak and IFI corrections	3.3	2.5	3.5	2.5
FSR (pair production)	3.6	0.8	4.4	0.8
Total	4.9	2.6	5.6	2.6

PDF uncertainties:

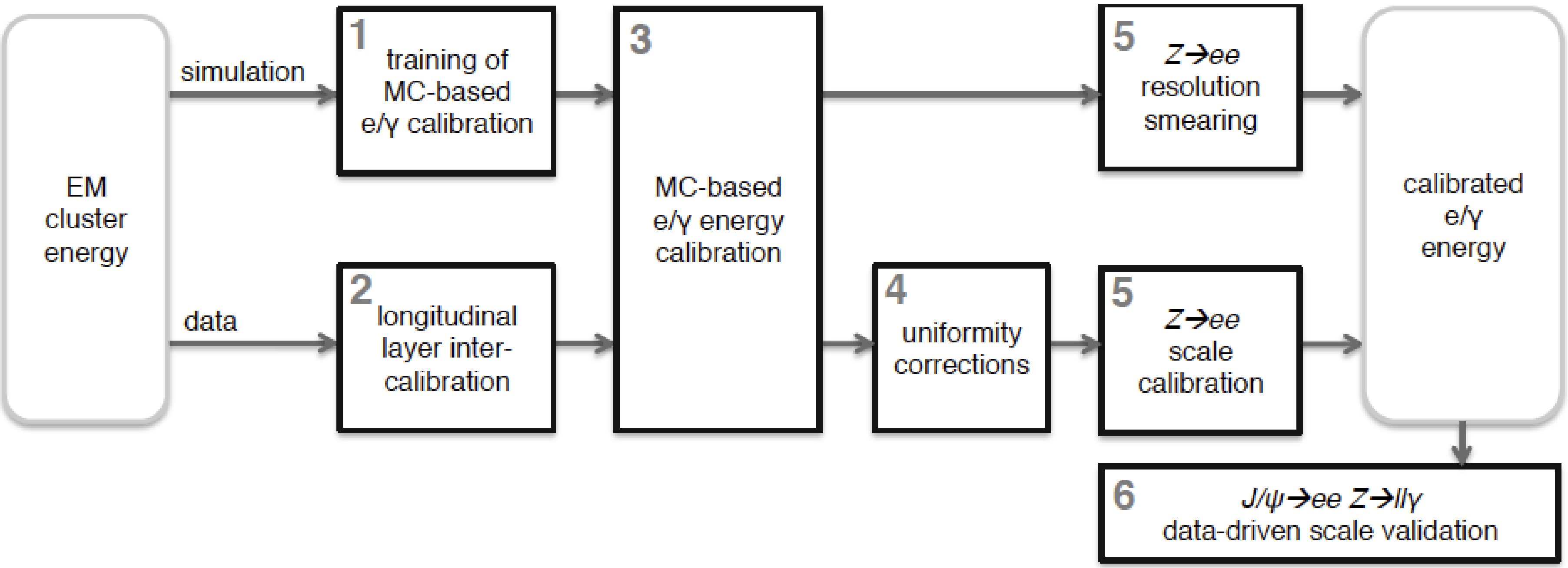
- PDF variations of CT10nnlo applied to rapidity, Ai, p_T^W
- Envelope taken from CT14 and MMHT2014 ~3.8 MeV

W-boson charge	W^+		W^-		Combined	
Kinematic distribution	p_T^ℓ	m_T	p_T^ℓ	m_T	p_T^ℓ	m_T
δm_W [MeV]						
Fixed-order PDF uncertainty	13.1	14.9	12.0	14.2	8.0	8.7
AZ tune	3.0	3.4	3.0	3.4	3.0	3.4
Charm-quark mass	1.2	1.5	1.2	1.5	1.2	1.5
Parton shower μ_F with heavy-flavour decorrelation	5.0	6.9	5.0	6.9	5.0	6.9
Parton shower PDF uncertainty	3.6	4.0	2.6	2.4	1.0	1.6
Angular coefficients	5.8	5.3	5.8	5.3	5.8	5.3
Total	15.9	18.1	14.8	17.2	11.6	12.9

QCD

Experimental corrections: Electron

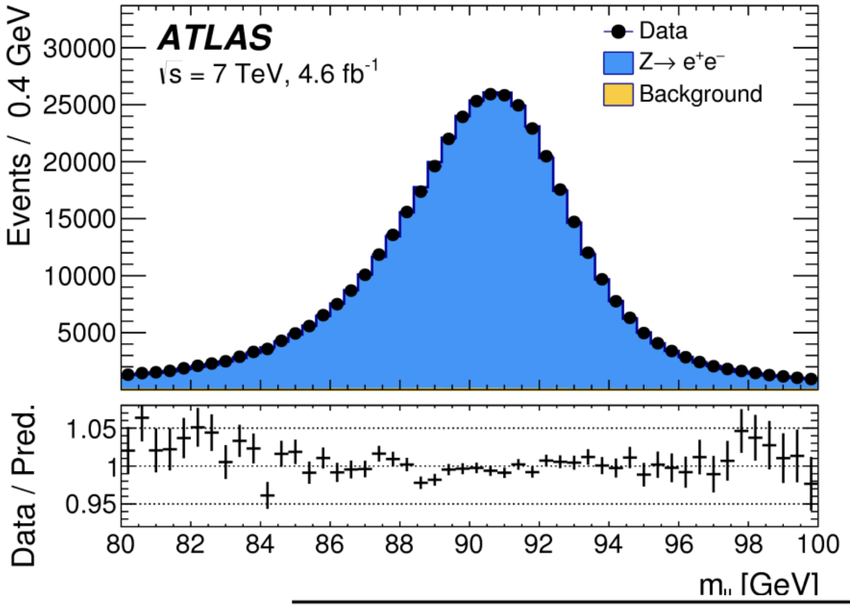
Eur.Phys.J.C 74 (2014) 3071

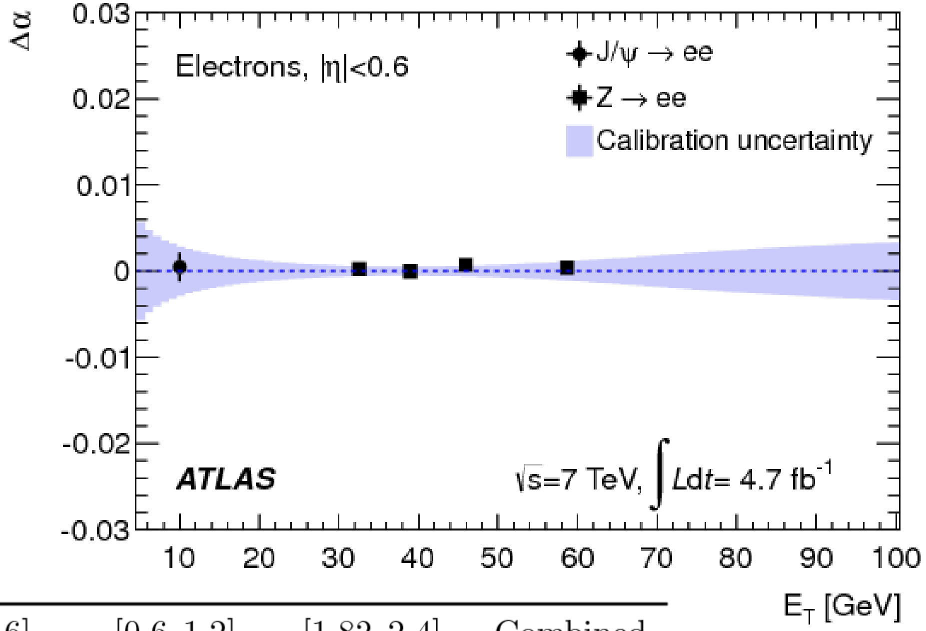


To achieve the highest precision, $1.2 < |\eta| < 1.82$ has been excluded as the amount of passive material
In front of the calorimeter with significant systematics.

Electron selection efficiency as function of p_T and η : Eur. Phys.J.C 74 (2014) 2941

Experimental corrections:　Electron





$\lvert\eta_\ell\rvert$ range	[0.0, 0.6]		[0.6, 1.2]		[1.82, 2.4]		Combined	
Kinematic distribution	p_T^ℓ	m_T	p_T^ℓ	m_T	p_T^ℓ	m_T	p_T^ℓ	m_T
δm_W [MeV]								
Energy scale	10.4	10.3	10.8	10.1	16.1	17.1	8.1	8.0
Energy resolution	5.0	6.0	7.3	6.7	10.4	15.5	3.5	5.5
Energy linearity	2.2	4.2	5.8	8.9	8.6	10.6	3.4	5.5
Energy tails	2.3	3.3	2.3	3.3	2.3	3.3	2.3	3.3
Reconstruction efficiency	10.5	8.8	9.9	7.8	14.5	11.0	7.2	6.0
Identification efficiency	10.4	7.7	11.7	8.8	16.7	12.1	7.3	5.6
Trigger and isolation efficiencies	0.2	0.5	0.3	0.5	2.0	2.2	0.8	0.9
Charge mismeasurement	0.2	0.2	0.2	0.2	1.5	1.5	0.1	0.1
Total	19.0	17.5	21.1	19.4	30.7	30.5	14.2	14.3

Experimental corrections: Muon

[Eur.Phys.J.C 74 (2014) 3130]

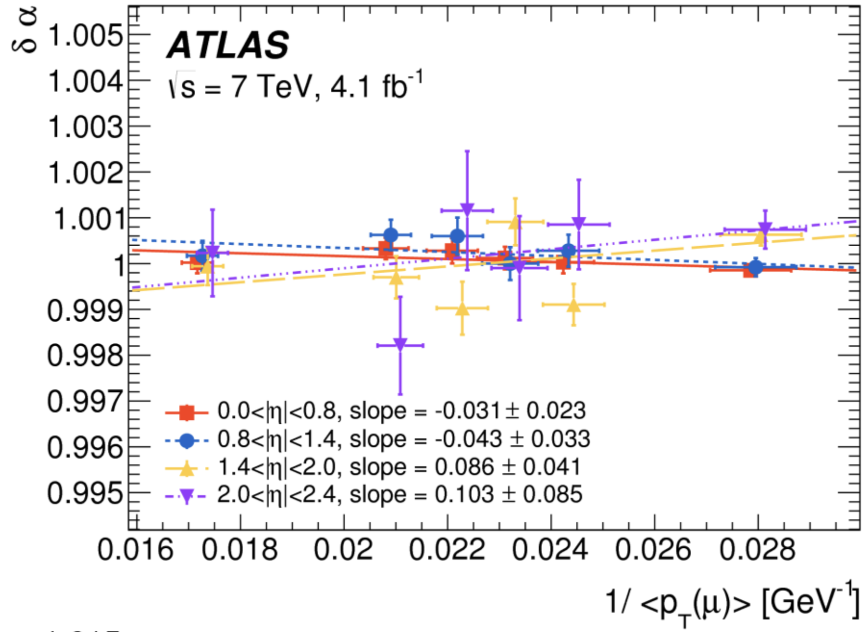
Muon identified using combined inner detector + muon spectrometer.
tracks, momentum measurement from ID only.

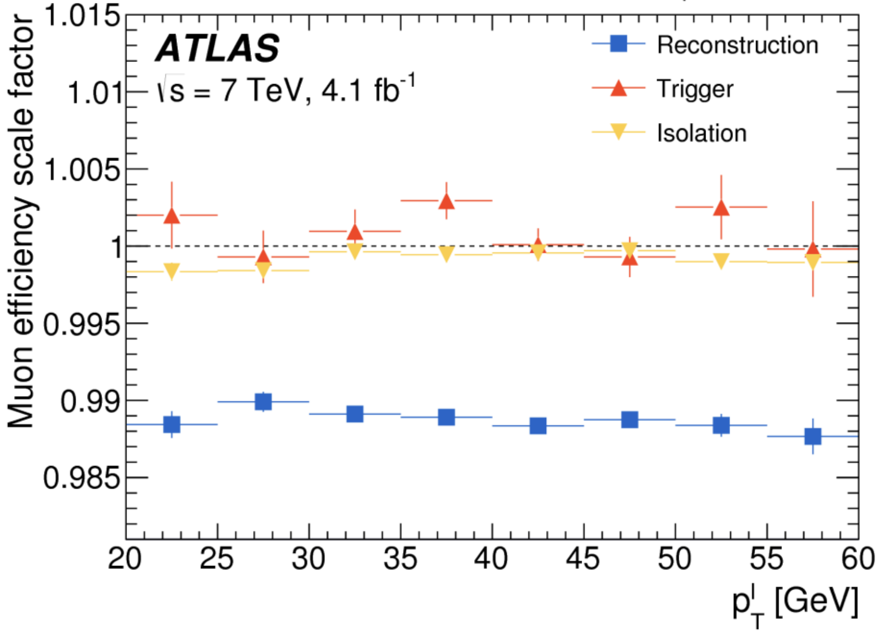
Calibration factors for ID-only muons derived from Z—>$\mu\mu$ and sagitta bias charge-dependent corrections

$$p_T^{\mathrm{MC,corr}} = p_T^{\mathrm{MC}} \times [1 + \alpha(\eta,\phi)] \times \left[1 + \beta_{\mathrm{curv}}(\eta) \cdot G(0,1) \cdot p_T^{\mathrm{MC}}\right]$$

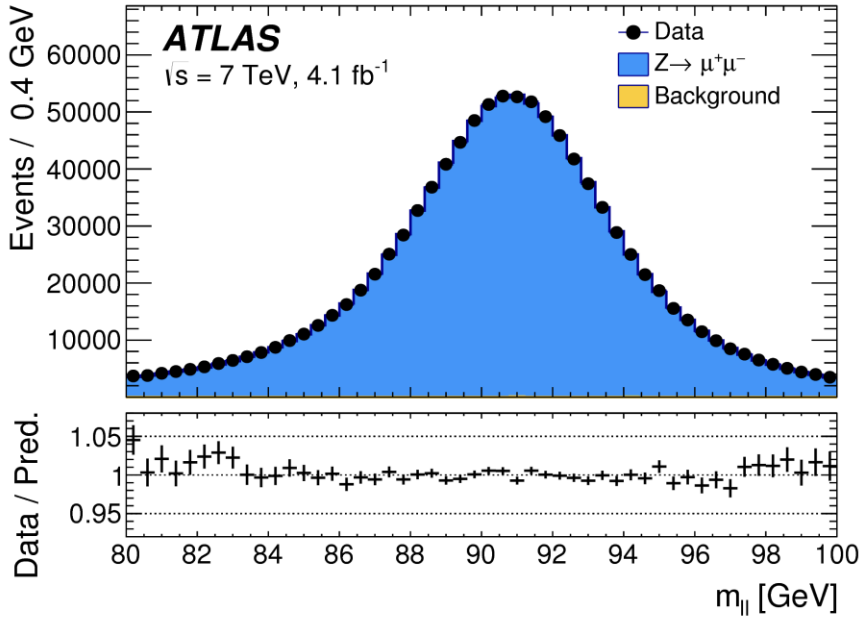
$$p_T^{\mathrm{data,corr}} = \frac{p_T^{\mathrm{data}}}{1 + q \cdot \delta(\eta,\phi) \cdot p_T^{\mathrm{data}}}$$

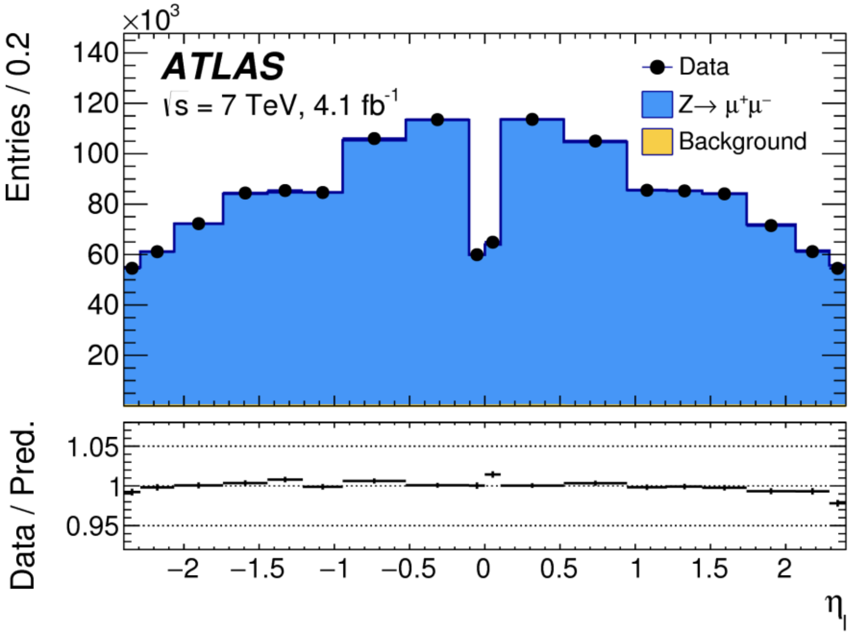
Muon trigger/id/iso efficiency corrections data/MC evaluated in bins of p_T and η and charge.
Dominant uncertainty is the statistical uncertainty of the Z sample.





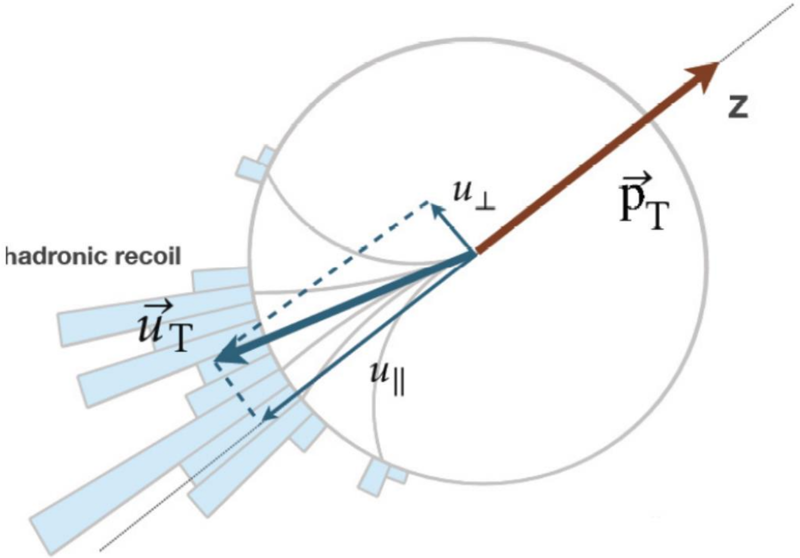
Experimental corrections: Muon





$\lvert\eta_\ell\rvert$ range	[0.0, 0.8]		[0.8, 1.4]		[1.4, 2.0]		[2.0, 2.4]		Combined	
Kinematic distribution	p_T^ℓ	m_T	p_T^ℓ	m_T	p_T^ℓ	m_T	p_T^ℓ	m_T	p_T^ℓ	m_T
δm_W [MeV]										
Momentum scale	8.9	9.3	14.2	15.6	27.4	29.2	111.0	115.4	8.4	8.8
Momentum resolution	1.8	2.0	1.9	1.7	1.5	2.2	3.4	3.8	1.0	1.2
Sagitta bias	0.7	0.8	1.7	1.7	3.1	3.1	4.5	4.3	0.6	0.6
Reconstruction and isolation efficiencies	4.0	3.6	5.1	3.7	4.7	3.5	6.4	5.5	2.7	2.2
Trigger efficiency	5.6	5.0	7.1	5.0	11.8	9.1	12.1	9.9	4.1	3.2
Total	11.4	11.4	16.9	17.0	30.4	31.0	112.0	116.1	9.8	9.7

Experimental corrections: Hadronic Recoil

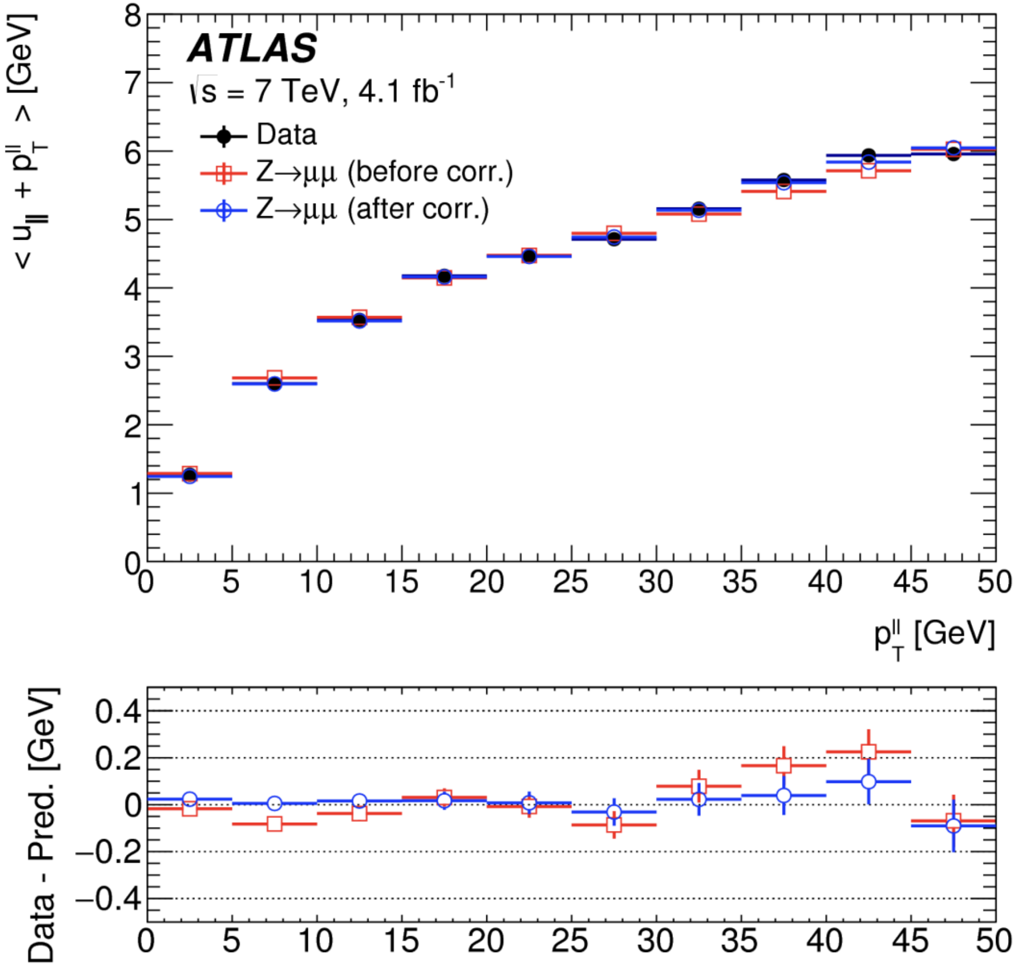


Vector sum of the momenta of all clusters measured in the calorimeters excluding energy deposits associated with the decay leptons

$$\overrightarrow{u_T} = \sum \vec{E}_T$$

$$\vec{E}_T^{Miss} = -(\overrightarrow{u_T} + \vec{p}_T^{\,lep})$$

Calibrate the scale (resolution) of the recoil using $u_{||}$ ($u_\perp$) from Z events



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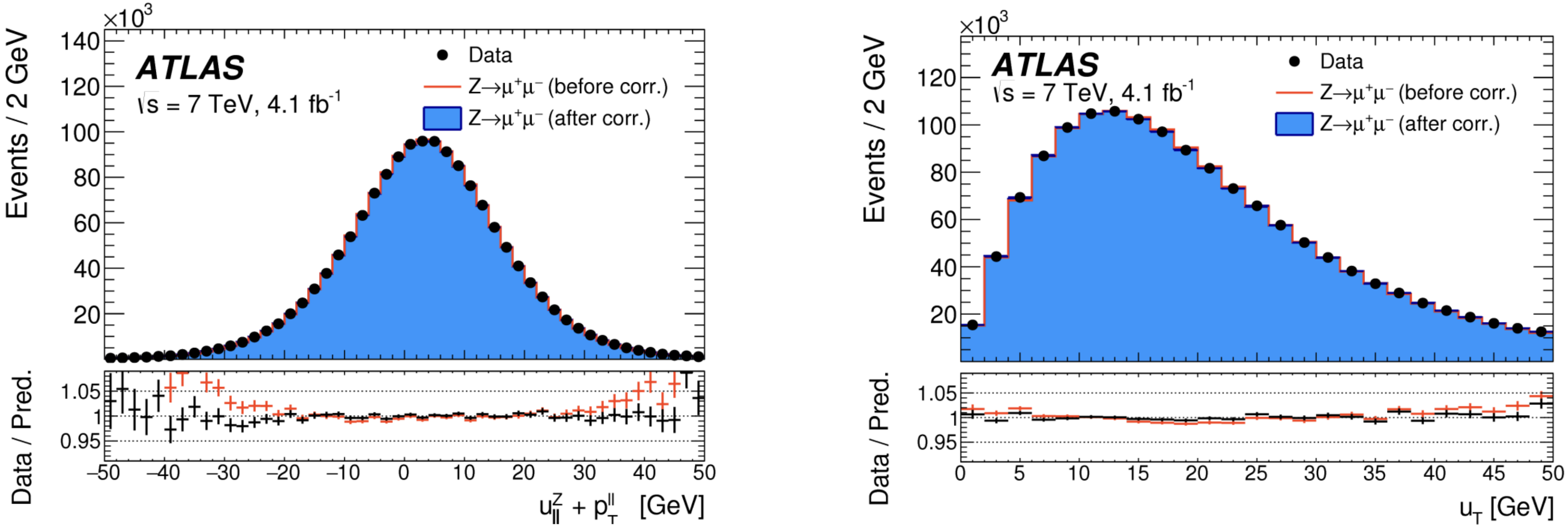
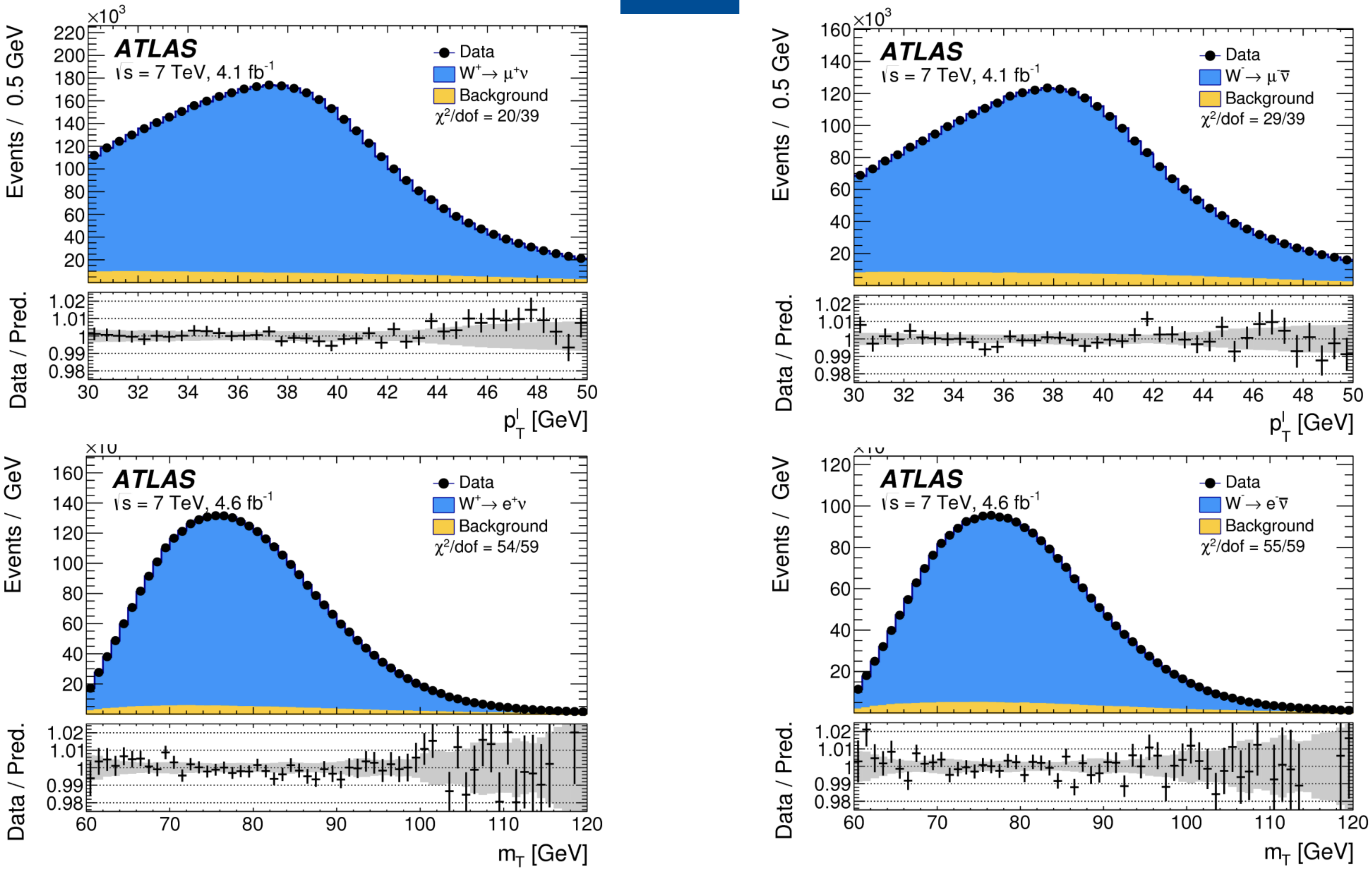
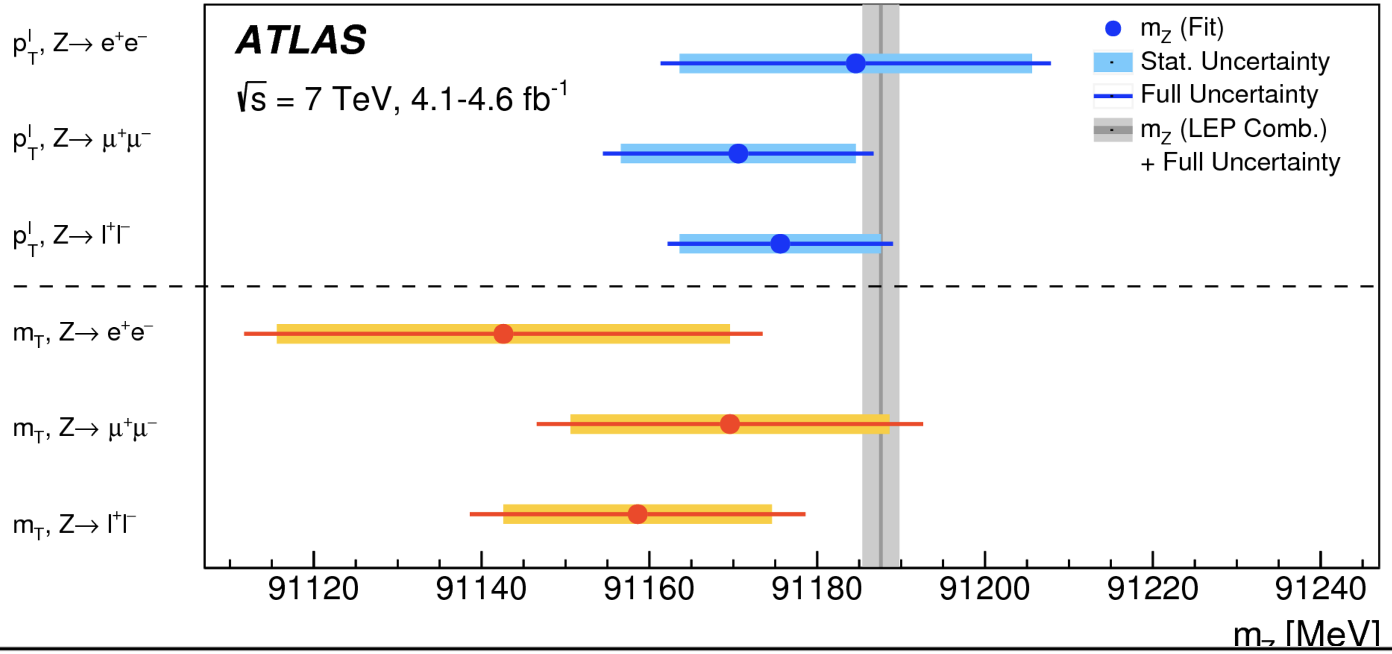


W-boson charge	W^+		W^-		Combined	
Kinematic distribution	p_T^ℓ	m_T	p_T^ℓ	m_T	p_T^ℓ	m_T
δm_W [MeV]						
$\langle\mu\rangle$ scale factor	0.2	1.0	0.2	1.0	0.2	1.0
$\Sigma\bar{E}_T$ correction	0.9	12.2	1.1	10.2	1.0	11.2
Residual corrections (statistics)	2.0	2.7	2.0	2.7	2.0	2.7
Residual corrections (interpolation)	1.4	3.1	1.4	3.1	1.4	3.1
Residual corrections ($Z \rightarrow W$ extrapolation)	0.2	5.8	0.2	4.3	0.2	5.1
Total	2.6	14.2	2.7	11.8	2.6	13.0

W mass-sensitive distributions



Z mass validation

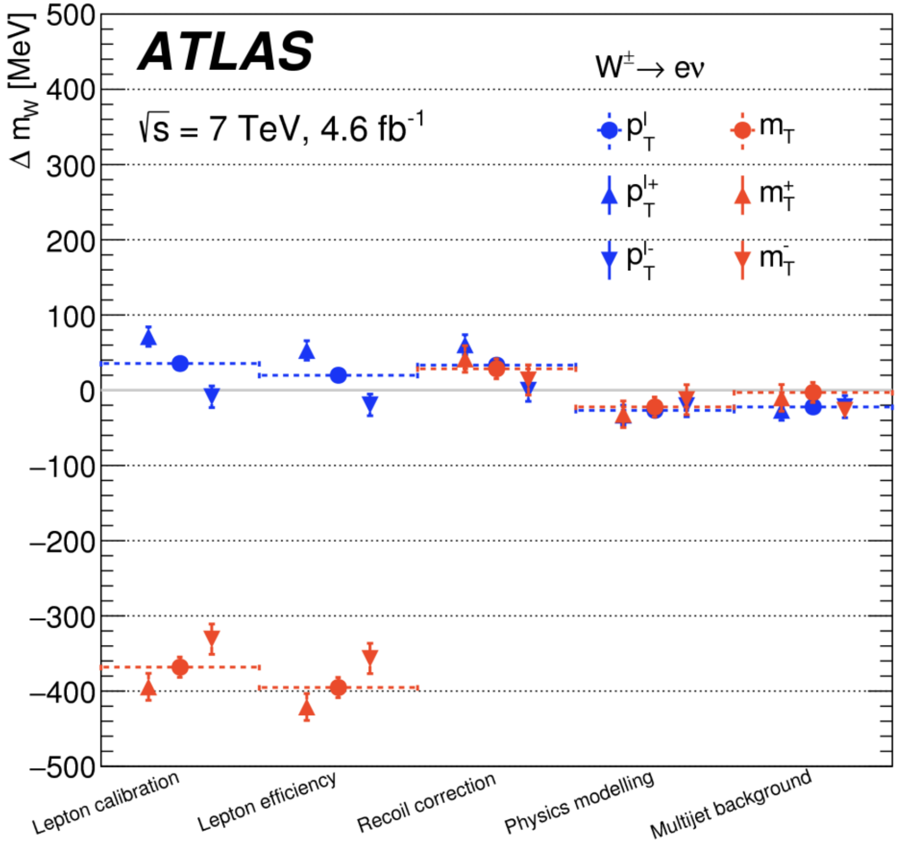


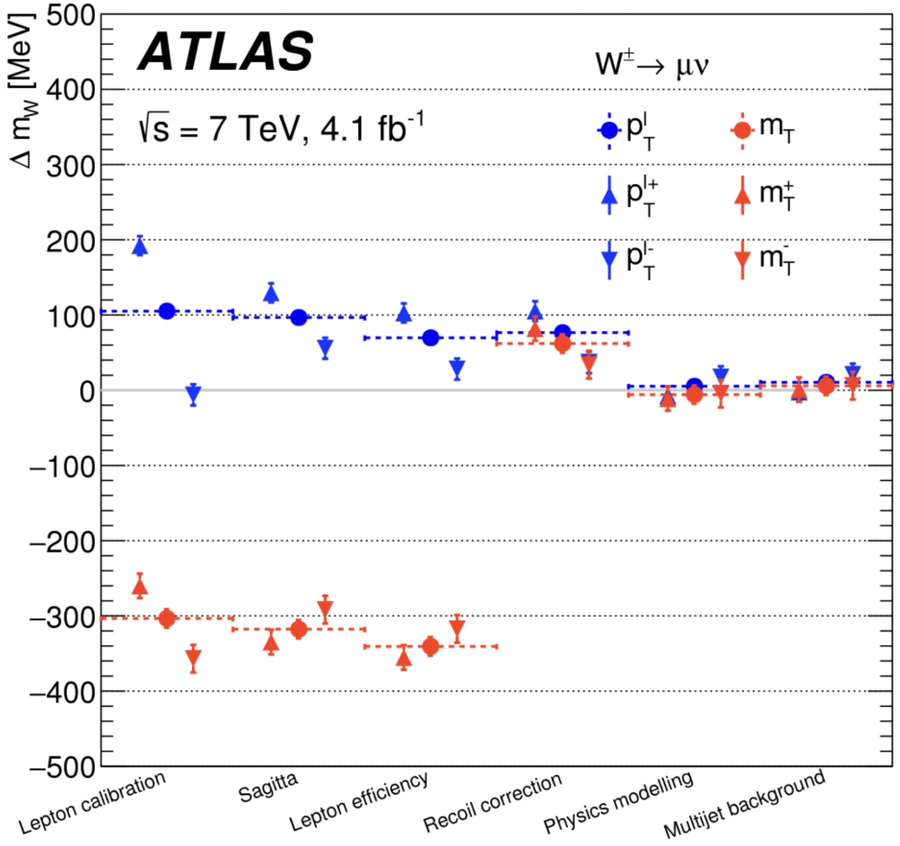
Lepton charge	ℓ^+		ℓ^-		Combined	
Distribution	p_T^ℓ	m_T	p_T^ℓ	m_T	p_T^ℓ	m_T
Δm_Z [MeV]						
$Z \to ee$	$13 \pm 31 \pm 10$	$-93 \pm 38 \pm 15$	$-20 \pm 31 \pm 10$	$4 \pm 38 \pm 15$	$-3 \pm 21 \pm 10$	$-45 \pm 27 \pm 15$
$Z \to \mu\mu$	$1 \pm 22 \pm 8$	$-35 \pm 28 \pm 13$	$-36 \pm 22 \pm 8$	$-1 \pm 27 \pm 13$	$-17 \pm 14 \pm 8$	$-18 \pm 19 \pm 13$
Combined	$5 \pm 18 \pm 6$	$-58 \pm 23 \pm 12$	$-31 \pm 18 \pm 6$	$1 \pm 22 \pm 12$	$-12 \pm 12 \pm 6$	$-29 \pm 16 \pm 12$

Results are consistent with the combined LEP value of m_Z within experimental uncertainties

Summary of corrections

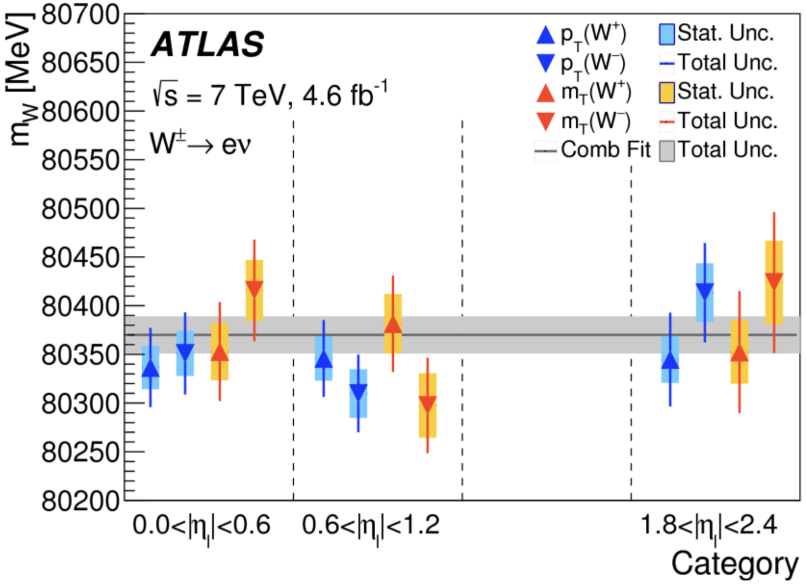
After all corrections are applied, consistent results are achieved between different channels, observables, categories, charges and only after, results were unblinded.

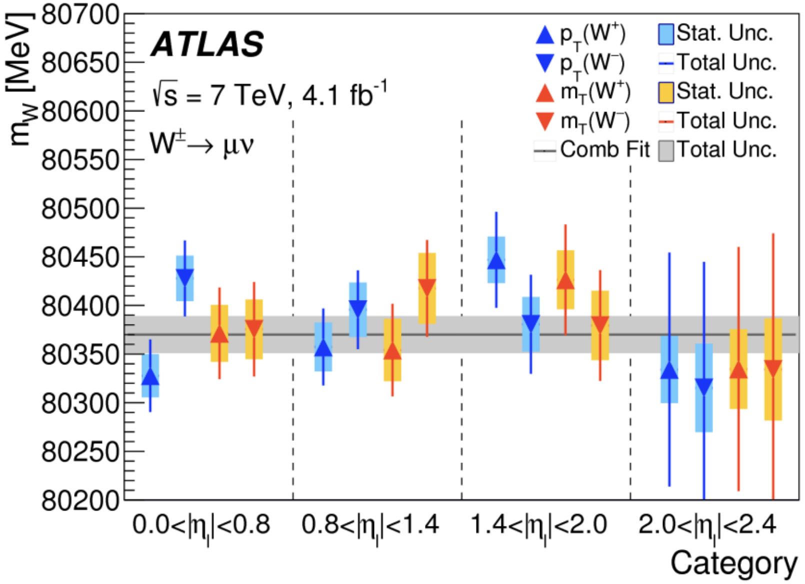


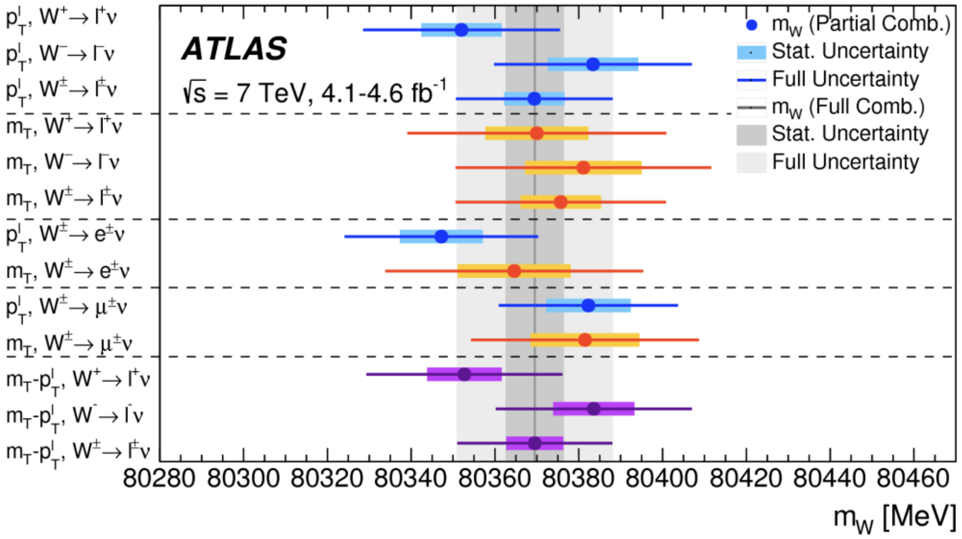


Consistency of the results

The consistency of the results was checked in the different categories but also in different pileup, recoil bins





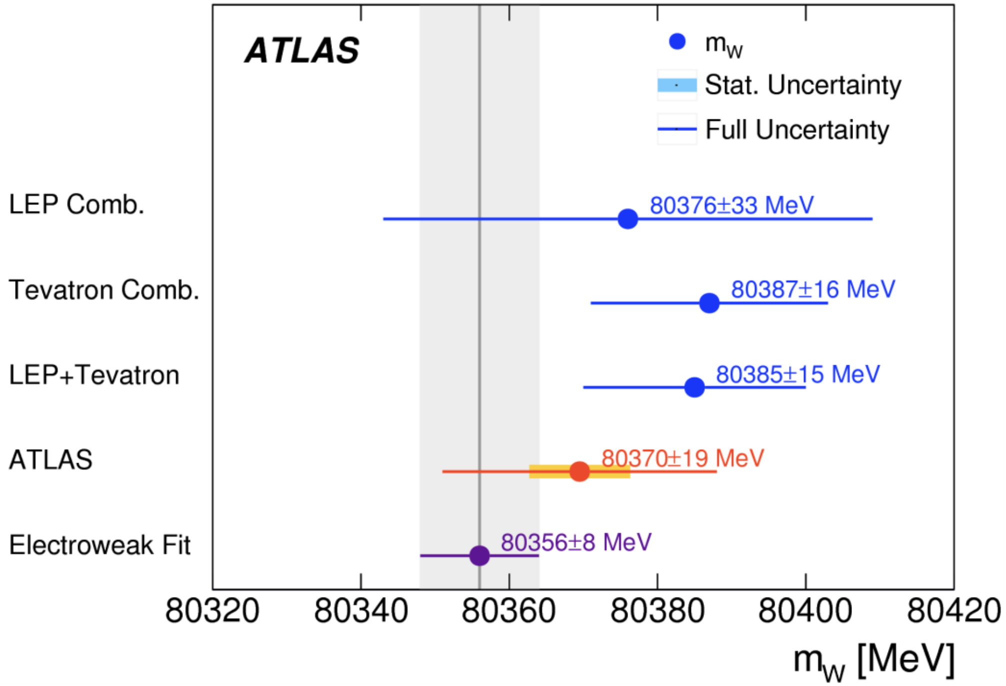


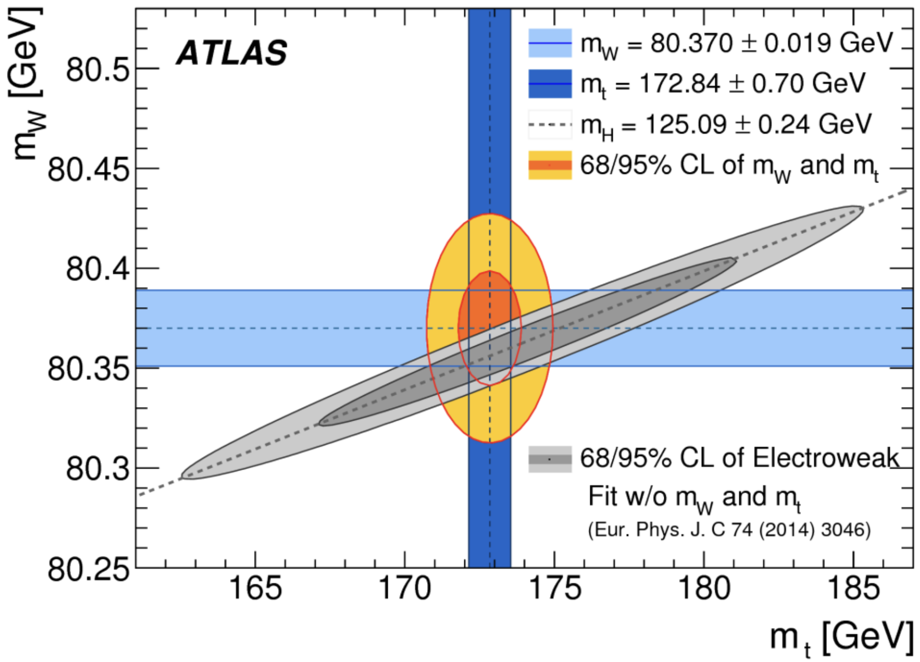
Run-I result

consistent with the SM expectation

$$m_W = 80369.5 \pm 6.8\,\text{MeV}(\text{stat.}) \pm 10.6\,\text{MeV}(\text{exp. syst.}) \pm 13.6\,\text{MeV}(\text{mod. syst.})$$
$$= 80369.5 \pm 18.5\,\text{MeV},$$

Combined categories	Value [MeV]	Stat. Unc.	Muon Unc.	Elec. Unc.	Recoil Unc.	Bckg. Unc.	QCD Unc.	EWK Unc.	PDF Unc.	Total Unc.	χ^2/dof of Comb.
m_T-p_T^ℓ, $W^\pm$, e-μ	80369.5	6.8	6.6	6.4	2.9	4.5	8.3	5.5	9.2	18.5	29/27





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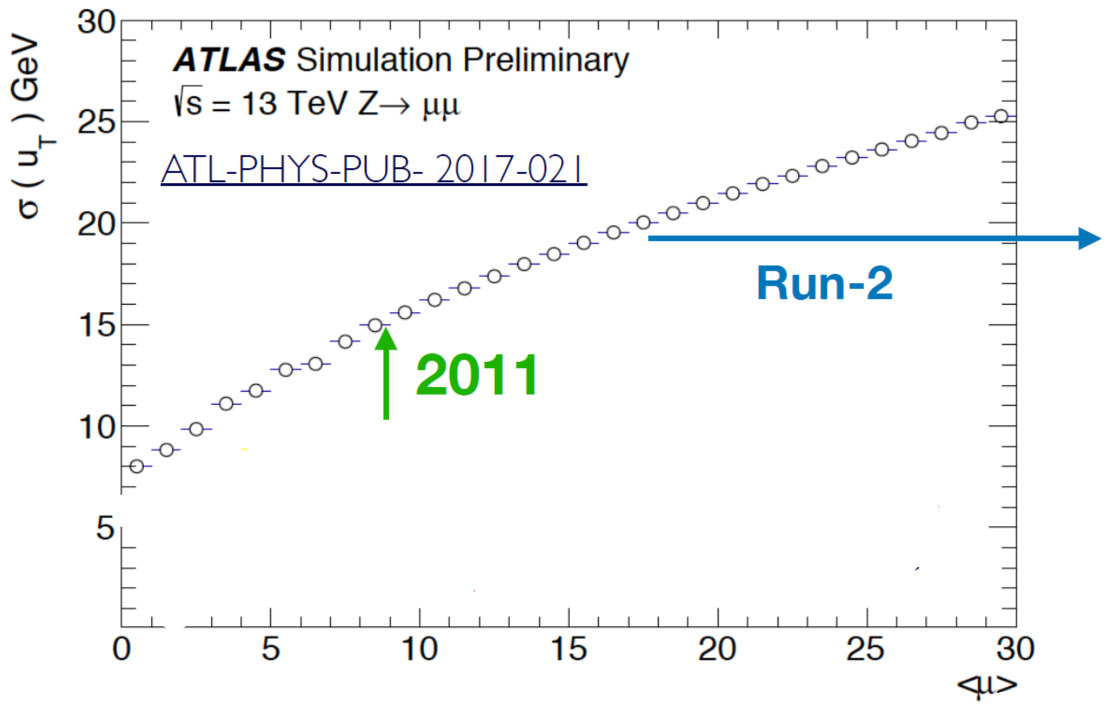
- **W mass @ ATLAS Run-II & future prospects**

Limit in 7-TeV measurement:

Recoil energy resolution is significantly worse when pileup grows:



Recoil uncertainty on mW:

W^+		W^-		Combined	
p_T^ℓ	m_T	p_T^ℓ	m_T	p_T^ℓ	m_T
2.6	14.2	2.7	11.8	2.6	13.0

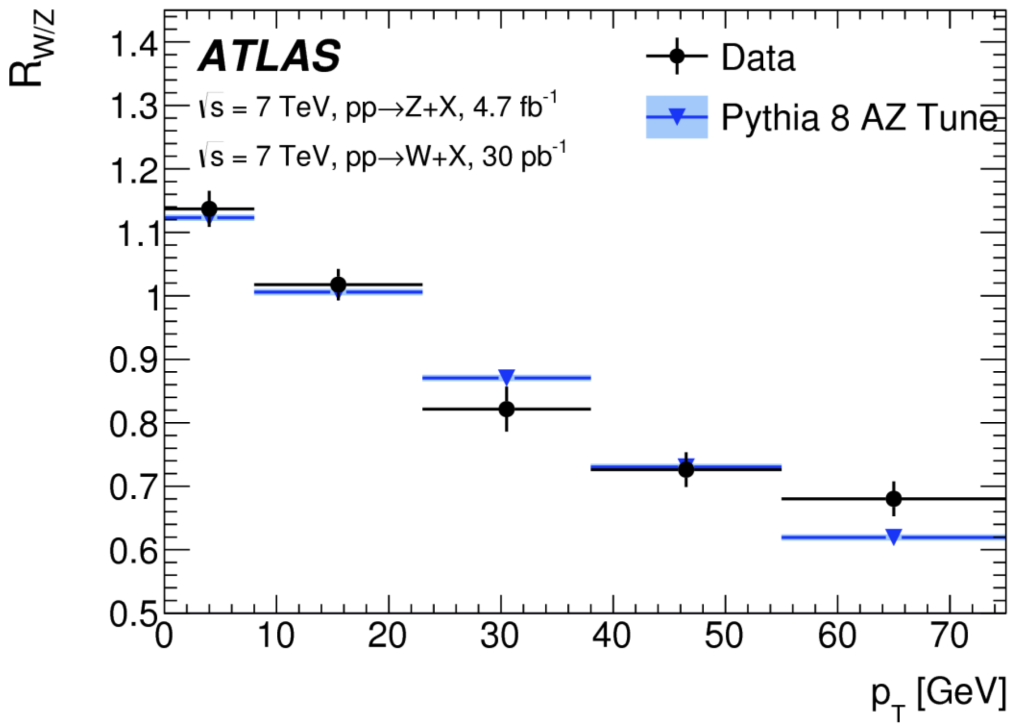
M_T^W has best sensitivity to W mass, which was affected due to the unavoidable recoil calibration problem in Run-I data.

Reduction of p_T^W uncertainty

The measurement to p_T^W with uncertainty < 1% in bins of ~5 GeV will untangle the mechanisms for both resummation and re-tune parton shower, and half the corresponding uncertainty (6 MeV -> 3 MeV).

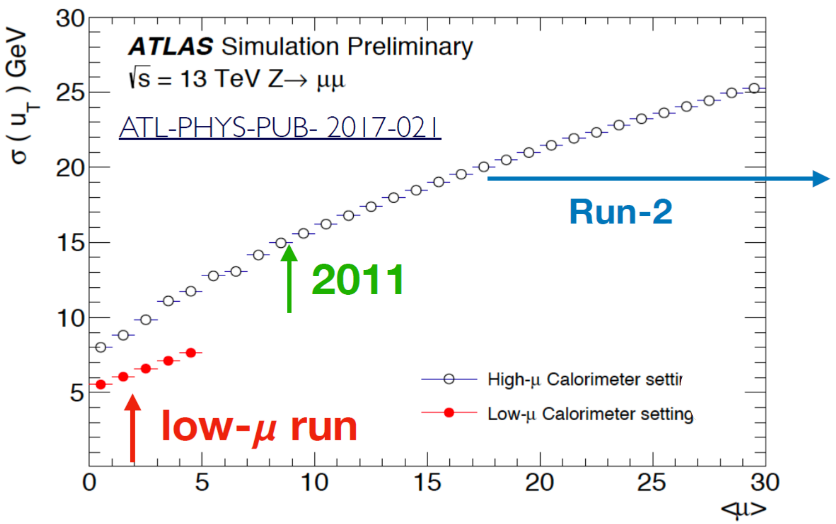
Published p_T^W and p_T^Z ratio:

Phys. Rev. D 85, 012005 arXiv:1701.07240



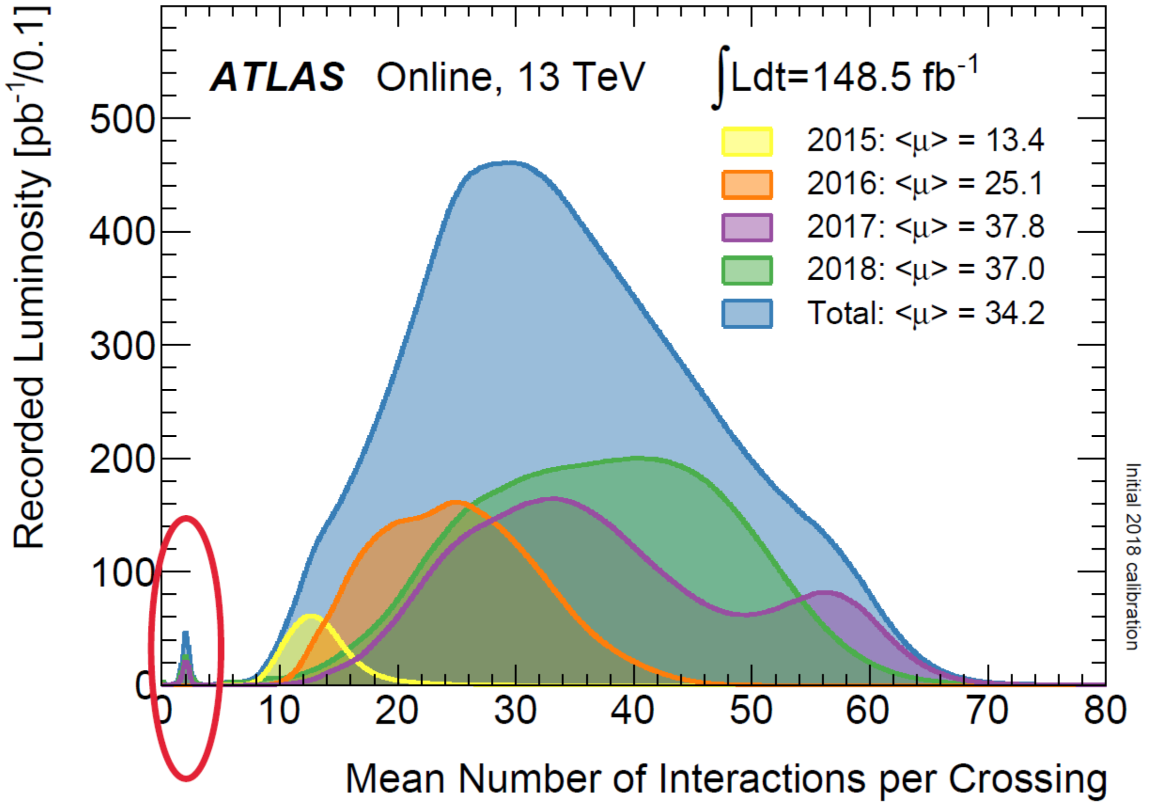
Limited precision of the data (~3%), and broad bin width (~8 GeV) limit the impact of these measurements on the systematic uncertainty.

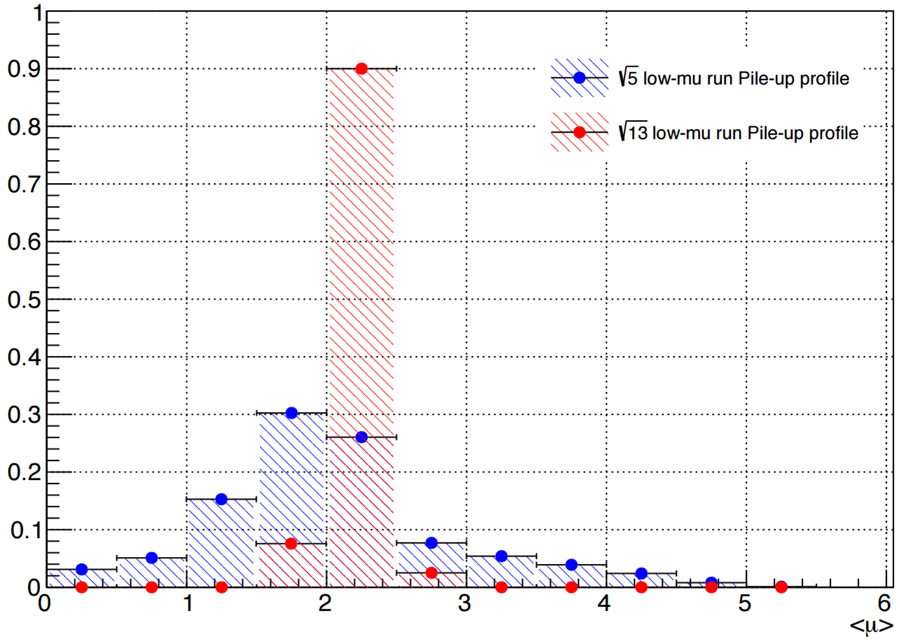
The target precision is only achievable when recoil resolution halved.



Special requested Low-pile-up Run:

A magic to improve W-boson precision!





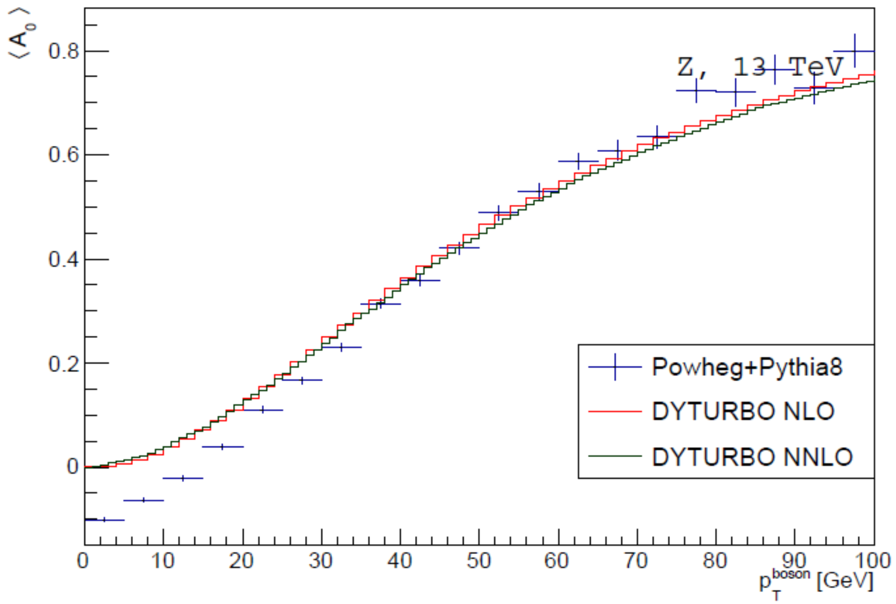
- 13TeV: 155 pb^{-1} (2017 Nov.) + 193 pb^{-1} (2018 Jul.) $\sim$ 4M W candidates,
- 5TeV: 25 pb^{-1}(2015) $\Rightarrow$ 258 pb^{-1} (2017 Nov.) $\sim$ 1.5M W candidates

On-going studies:

- W and Z transverse momentum measurements at 5 and 13 TeV
- W and Z production cross-section measurements at 5 and 13 TeV
  - Best precision at the two energies -> improvement to PDF
- W-mass measurement using low-pileup data + reanalysis of 7-TeV data
  - Benefiting from improved recoil / QCD modelling / run-II experimental updates

Corrections and modellings applied:

- Zvtx reweighting (z-position of the primary vertex);
- Primary vertex selection efficiency;
- Rapidity correction by Powheg + CT10nnlo;
- NNLO + angular coefficients by DYTURBO;
- EW FSR by Photos++; ISR by Pythia;
- In-situ parameter functions to correct p_T



W mass at Run-II? What to expect?

Experimental improvements; **theoretical improvements;**

Preliminary Estimation
NO ANY DATA!

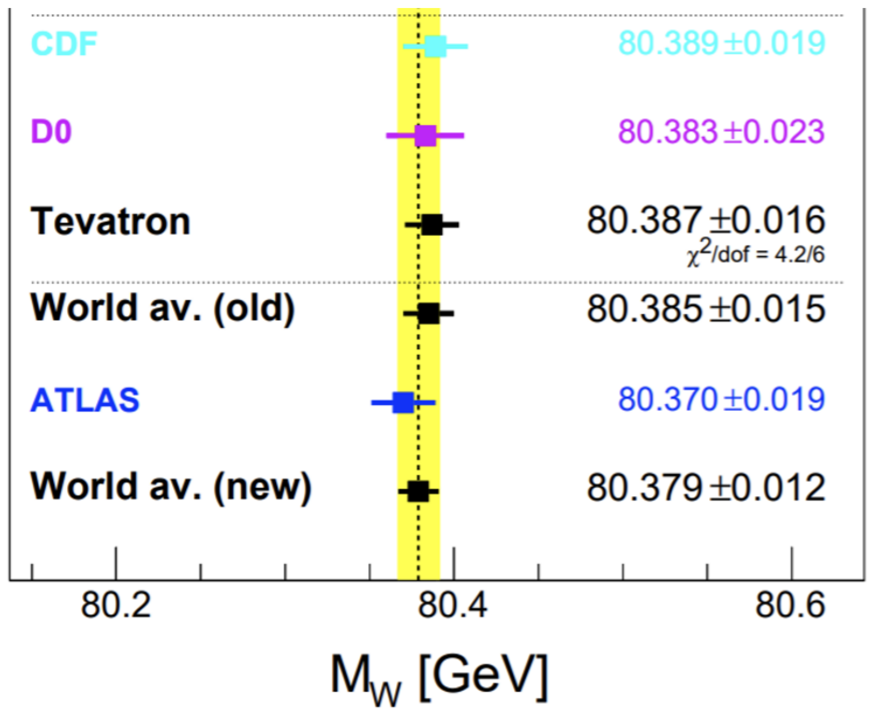
Annotation	Data sample	7TeV, $\mu \sim 9$	13TeV, $\mu \sim 2$	5TeV, $\mu \sim 2$
	Luminosity	4.5 fb^{-1}	0.3 fb^{-1}	0.2 fb^{-1}
	Nb. of candidates	$\sim 15 \times 10^6$	$\sim 4 \times 10^6$	$\sim 1.4 \times 10^6$
	Observables	p_T^{lep}	$p_T^{lep}+m_T^W$	$p_T^{lep}+m_T^W$
Combine two observables	Stat.	7	8	12
	Lepton calibration	7	7	7
New Run-II strategies & extrapolation	Lepton efficiencies	7	5	5
Low-mu, but limited by stat	Recoil calibration	3	5(7)	3(8)
Optimized MJ procedure	Backgrounds	5	3	2
New prediction at NNLO	EW	5	2	2
This measured p_T^W	QCD(p_T^W)	6	<3	<3
Fixed angular coefficient	QCD(Spin)	6	<3	<3
This measured Xs	PDF	9	6	6
	Total	19	15	17

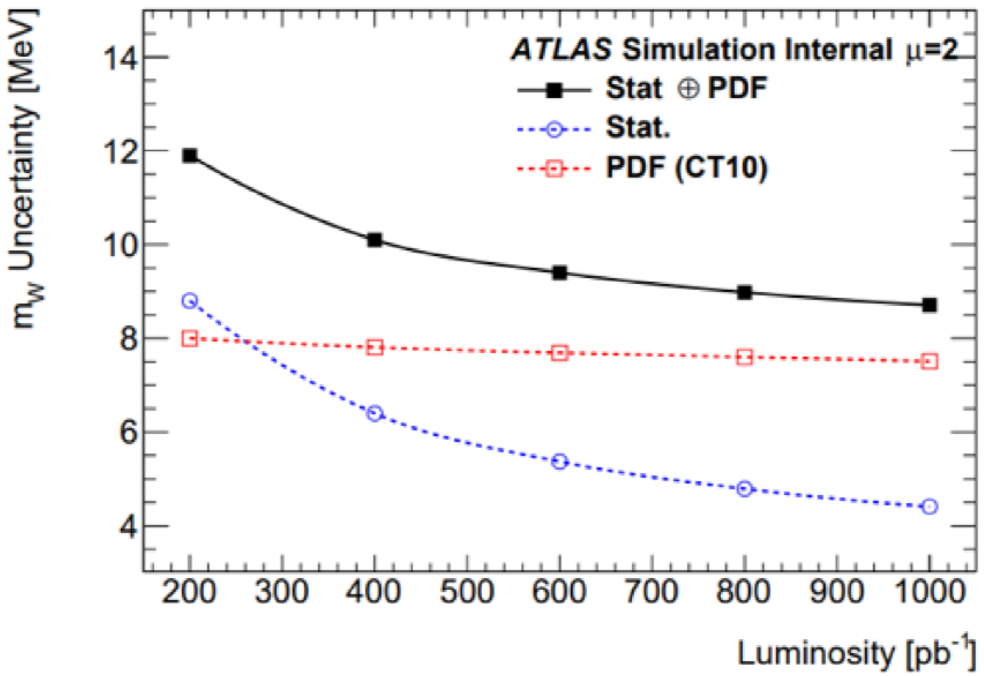
Target: comparable experimental uncertainty, significantly improved theoretical uncertainty

Prospects in W mass precision

The most urgent tasks to improve W mass precision is the finalization of low-mu p_T^W and Xs measurements.
Application of LLH fit (δM as NP) is likely to contribute the most important methodological improvements.

- All theoretical improvements is applicable to 7-TeV measurement: 19 MeV to < 15 MeV
- Further combination of 7-TeV measurement and low-mu measurement





Extra Weeks Of Low Mu Run

Summary

- The first LHC measurement of mW = 80370+/-19 MeV is public after many years of effort in the ATLAS collaboration.
- The central value is consistent with the SM prediction and world average (2017)

- Run-II low-pileup data has potential in bring critical theoretical improvement to W mass at LHC

- The low lumi of low-pileup data is becoming one main limit which could be solved with more low-mu run.